

TITLE OF THE INVENTION

5 HOLDER FOR ELECTRICAL BRUSHES AND ANCILLARY CABLES

CROSS-REFERENCES TO RELATED APPLICATIONS

- This application claims priority to U.S. Provisional Application Serial No. 60/130,880, filed April 23, 1999, entitled "Liquid Metal/Compressed Gas Brush Holder."
- 10 This application is also related to co-pending international application Serial No. 09/147,100, filed on April 4, 1997, entitled "Continuous Metal Fiber Brushes." The above-noted applications are herein incorporated by reference.

BACKGROUND OF THE INVENTION

15 Field of the Invention

*This invention relates to electrical brush holders whose function is: (i) to maintain the running surface of any given brush in a steady, predetermined position during relative tangential motion between the brush and its substrate (i.e., commonly a slip ring or commutator), (ii) to apply a predetermined, nearly constant mechanical pressure between the brush running surface and the substrate while the brush may wear, and (iii) to conduct electrical current to or from the brush.*

The electrical brushes at issue include all conventional "monolithic" brushes (i.e. made in one piece of graphite or graphite-metal mixtures), as well as metal fiber brushes disclosed in U.S. Patent Nos. 4,358,699 and 4,415,635, and in the co-pending international patent application Serial No. 09/147,100. Additionally, they include foil brushes as described

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in the publication "Production and Performance of Metal Foil Brushes," P.B. Haney, D. Kuhlmann-Wilsdorf and H. G. F. Wilsdorf, WEAR, 73 (1981), pp. 261-282. The present invention is particularly useful for electrical metal fiber brushes in motors and generators when operating at high current densities, especially in homopolar motors/generators. The 5 present invention includes the use of various technologies referenced and described in the above-noted U.S. Patents and Applications, as well as described in the references identified in the appended LIST OF REFERENCES and cross-referenced throughout the specification by reference to the corresponding number, in brackets, of the respective references listed in the LIST OF REFERENCES, the entire contents of which, including the related patents and 10 applications listed above and the references listed in the LIST OF REFERENCES, are incorporated herein by reference.

#### Discussion of the Background

Sliding electrical contacts, i.e., "brushes," conduct electrical current between solids, 15 very preponderantly metals, in relative motion. Brushes are in widespread use in various types of electric motors and generators and are also widely used in less common but numerous special applications, e.g. telemetry devices and rotating antennae. Even while to date the traditional "monolithic" (i.e., in the form of a solid piece) graphite-based (i.e., including compacted graphite or various metal-graphite mixtures) brushes are 20 overwhelmingly frequent, they have a number of technological limitations. Specifically, monolithic graphite-based brushes cannot be reliably used over extended periods of time at current densities above about 30Amp/cm<sup>2</sup>, nor at sliding speeds above about 25 m/sec. Further, as a coarse estimate, they waste about one watt per ampere conducted across the

brush-substrate interface (i.e. the equivalent of one Volt) in terms of Joule and friction heat together. Further, monolithic brushes emit significant intensities of electromagnetic waves (i.e., they are electrically very noisy so as to interfere with radio and similar signal reception), and finally they wear into a powdery debris that can be highly detrimental in electrical 5 machinery, especially aboard submarines.

As a result of these shortcomings of traditional monolithic brushes, a number of otherwise very attractive technological developments are stymied for lack of electrical brushes which will conduct reliably over extended time periods, much higher current densities at low losses up to much higher speeds. Most importantly impacted are so-called "homopolar" motors and generators. They have potentially very high power densities and would be excellent for Navy as well as commercial ship drives, among others, but typically require current densities in excess of one hundred Amperes per cm<sup>2</sup> to be conducted across interfaces of metal parts relatively moving at sustained speeds up to 30 m/sec or even more while producing or requiring EMF's of only 20V or so. The requirements of homopolar machinery in terms of current densities and speeds can thus not be fulfilled by monolithic 10 brushes, and in any event a loss of 2 Volts per monolithic brush pair, i.e., in and out, is prohibitive for homopolar machines. 15

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In previous inventions, particularly in the Patent Application "Continuous Metal Fiber Brushes, [1]" the capabilities of metal fiber brushes, including multitudes of essentially parallel hair-fine metal fibers, are outlined. Metal fiber brushes are intrinsically capable of easily conducting the desired current densities and to do so up to at least 70 m/sec with a total loss in the order of 0.1 Volt per brush. At the same time such brushes are electrically very quiet. These superior qualities derive from large numbers of separate electric "contact spots,"

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~~namely at the fiber ends at the brush "working surface" sliding along the brush-substrate~~

A interface, through which the current is physically conducted on a microscopic scale. *That*  
current is conducted across solid interfaces only through a restricted number of contact spots,  
whose total area amounts to only fractions of one percent of the macroscopic area of contact,  
5 is a well-known general physical phenomenon. To a large extent the poor qualities of  
monolithic brushes arise from their small number of contact spots, namely in the order of ten  
per brush. As a result, the current flow lines in monolithic brushes are not rather uniformly  
distributed, as they are in metal fiber brushes, but they are "constricted" [2] at the few contact  
spots. This causes the corresponding "constriction resistance" that represents in the order of  
10 one third the resistance of monolithic brushes. This constriction resistance is eliminated in  
~~metal fiber brushes on account of their large number of contact spots.~~

The superiority of metal fiber brushes does not only derive from their thousands of  
evenly distributed contact spots, but also because at their contact spots, bare metal meets bare  
metal, ideally separated only by a double monomolecular layer of adsorbed water.

15 Fortuitously, this most favorable type of lubrication, which prevents cold-welding and  
accommodates the relative motion between brush and substrate at a "film resistivity" of only  
 $\sigma_f \approx 1 \times 10^{-12} \Omega m^2$  and average friction coefficient ( $\mu$ ) of about 0.3, establishes itself  
automatically at any modest ambient humidity, provided that the area of any one brush is not  
too large and there are gaps between the brushes so as to permit access of the moisture to the  
20 substrate and that undue contamination with oils, etc., is avoided. By contrast, monolithic  
brushes deposit a lubricating graphitic layer through which the current must flow at much  
higher electrical film resistivity and which typically is also overlaid by the already indicated  
film of adsorbed moisture [3]. Further, the body resistance of graphitic brushes can be

significant while it is always negligible for metal fiber brushes. Finally, monolithic brushes are hard and "bounce." At increasing speeds, the "brush bounce" must be counteracted by an increasingly strong pressure between brush and substrate at the correspondingly increased friction power loss. This syndrome limits the sliding speed of monolithic brushes to about 25 m/sec, as already indicated, whereas metal fiber brushes are intrinsically flexible (i.e., have a much larger "mechanical compliance"). Therefore, metal fiber brushes can and should be mechanically lightly loaded and can be operated to high speeds with minor friction heat loss.

Metal foil brushes closely resemble metal fiber brushes except they are composed not

of substantially parallel fibers but of thin parallel foils. Consequently, metal foil brushes typically have many fewer, but otherwise the same kind of, contact spots. Thus, metal foil brushes are very similar to metal fiber brushes but cannot match their attainable current densities, sliding speeds and low power losses. At any rate, foil brushes are based on the same principle as metal fiber brushes, namely, electrical contact to the substrate at a large number of microscopically small, bare metal-metal contact spots, optimally lubricated by a double monomolecular layer of adsorbed water. Hence, in terms of the number of contact spots per unit working surface area (i.e., "contact spot density"), and mechanical load per

contact spot, the same theory applies to metal foil as to metal fiber brushes.

*Jn<sup>5</sup> B<sup>3</sup> Cmt* > As stressed, on account of their different geometry, foil brushes include a substantially smaller density of contact spots than well-constructed metal fiber brushes. By numerical example, the working surface of a typical metal fiber brush constructed of  $d = 50\mu\text{m}$  copper wires of about  $f = 15\%$  packing fraction contains roughly 10,000 contact spots per  $\text{cm}^2$ , namely, one at each of the individually flexible fiber ends. In a foil brush with  $d_f = 25\mu\text{m}$  thick parallel foils and  $f = 50\%$  packing fraction, there are about 600 contact spots per  $\text{cm}^2$ ,

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~~located at the foil edges sliding on the substrate, with an estimated three contact spots per foil edge. Correspondingly, without suitable modifications of the substrate, foil brushes will be very superior to monolithic brushes, but fall short of metal fiber brushes.~~

In typical use, both types of brushes are expected to wear by similar length changes in

5 the course of their life times, e.g. several millimeters ( $1/4"$ ) or up to an inch, during which time the mechanical brush force should be kept roughly constant. The major differences between monolithic and metal fiber brushes include:

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- ~~lower mechanical pressure, namely several pounds per square inch for monolithic brushes, versus about 1 Newton per square centimeter  $\cong \frac{1}{2}$  pound per square inch for fiber brushes.~~
  - higher current densities, i.e., up to  $30 \text{ Amp/cm}^2 \cong 200 \text{ Amp/in}^2$  for monolithic brushes and up to  $300 \text{ Amp/cm}^2 \cong 2000 \text{ Amp/in}^2$  for fiber brushes,
  - at the indicated maximum tolerated current densities and speeds up to 70 m/sec, total losses of below 0.3V per ampere conducted, including friction and Joule heat, for fiber brushes and about 1 V/ampere conducted for monolithic brushes.
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Correspondingly, the mechanical stiffness as well as the electrical resistance of, and hence the electrical loss in, the current leads to or from the brushes, are always inconsequential for monolithic brushes but become very important for metal fiber brushes when used anywhere near their current carrying capability.

20 As a result, the mechanical force can be applied to monolithic brushes via springs or any other desired mechanical means, while the current is led to or from the brushes either through the same springs and/or through ordinary flexible electrical cabling connected in parallel with the brush force applicator. However, this is not a viable option for demanding

*and foil*

A applications of metal fiber brushes because 1) the weaker springs needed for them will unavoidably have an electrical resistance comparable to or higher than that of the brushes, unless they were to be cooled to cryogenic temperatures and even perhaps be made of a superconducting material, and 2) the incidental forces exerted on the brush by flexible cables 5 with adequately low electrical resistance above cryogenic temperatures will rival or exceed the applied spring force.

The problem to be solved for metal fiber brushes used at high current densities above cryogenic temperatures is therefore how to apply a controllable light brush pressure and at the same time to establish a low resistance electric contact to or from the brushes. A system with 10 these characteristics would in fact be applicable to any electrical brush, whether of metal fiber or monolithic type, under any running conditions, but it would be definitely necessary only *and for* for the indicated high-current-density use of metal fiber brushes.

#### SUMMARY OF THE INVENTION

15 Accordingly, one object of the present invention is to solve the above-noted and other problems.

Another object of the present invention is to provide a novel brush holder, which operates via hydrostatic pressure of a compressed material, such as a compressed gas and/or liquid metal.

20 Yet another object of the present invention is to provide a novel brush holder, which eliminates or reduces "brush brounce."

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Still another object of the present invention is to provide a novel brush holder, which provides a light <sup>substantially</sup> ~~or for~~ constant pressure to a fiber brush sliding against a substrate for extended periods of time.

Another object of the present invention is to provide a novel brush holder, which has ~~or for~~ low electrical resistance to improve the current densities generated by the fiber brush sliding against the substrate.

To achieve this and other objects, the present invention provides a novel electrical brush holder for applying a mechanical force to an electrical brush and for establishing electrical contact between the electrical brush and a current conducting element. The brush holder includes a first <sup>wall</sup> plate fastened to the current conducting element, a second <sup>wall</sup> plate fastened to the brush, and a sidewall lengthwise extendable in an axis direction of the brush. The sidewall cooperates with the first and second plates to form a volume defined by the first <sup>wall</sup> plate, the second <sup>wall</sup> plate and the sidewall. A fluidic medium is contained in the volume for applying a light <sup>substantially</sup> constant pressure to the brush.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

Figure 1A shows a brush holder disclosed in co-pending international application

Serial No. 09/147,100;

*Jns 2* > Figures 2A to 2C are schematic cross-sectional views of the brush holder according to

*B6* the present invention with one brush (Figure 2A) and two brushes (Figure 2B) attached to one base plate, and with two brushes attached to two base plates (Figure 2C);

Figures 3A and 3B are perspective views of Figure 2A in which a pressurized material

5 includes both a liquid metal and a compressed gas;

Figure 3C is a cross-sectional view of the brush holder in Figs. 3A and 3B, but with a different configuration for the compressed gas and an outer wall strengthened by spiral tubing;

Figure 3D is a cross-sectional view of the brush holder of Figure 3B including a

10 flexible connection to a pressurized gas reservoir to maintain a gas pressure;

Figures 4A and 4B are cross-sectional views of the brush holder in Figs. 3B and 3D,

*A* but include a telescoping outer wall showing a position at the start position of a brush operation (Figure 4A) and after significant brush wear (Figure 4B);

Figure 5 is a perspective view of a brush holder in Figs. 3A to 3D, but includes a set 15 of rods for restraining the flexible side wall from lateral motions;

*Jns 3* > Figures 6A and 6B are cross-sectional views of brush holders including wedge-shaped

*B7* top and bottom walls plates to facilitate orienting the brush relative to the substrate;

Figures 7A to 7C are perspective views of liquid metal cables made of flexible and extendable tubing filled with liquid metal and fitted with different electrical connectors;

*Jns 4* > Figures 8A to 8C are cross-sectional views of different brush holders in which the 20 current is conducted through liquid metal cables and the brush force is supplied by mechanical springs; and

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Figures 9A to 9B are cross-sectional views of brush holders in which the current is conducted through a highly flexible cable of metal fibers and the brush force is supplied by compressed gas.

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## DESCRIPTION OF THE PREFERRED EMBODIMENTS

### a) Relationships Between Electrical Resistance and Mechanical Stiffness for Combination Springs/Current Supplies or Cables

#### Metal Springs for Simultaneous Brush Loading and Current Connection

In future high performance applications of metal fiber brushes, it is envisaged that currents of up to 2000 Amperes will be conducted through brushes of up to 1 square inch of working surface (e.g., a brush foot print on a slip ring), while the brush is pressed against the substrate (i.e., in this case a slip ring, with a brush pressure in the range of 1 Newton per square centimeter (i.e., roughly one pound per square inch). The brush pressure is intended to be maintained within a factor of two or three, even while the brush slides at a high speed, up to more than 100 mph, and in course of time may shorten in length through wear by up to about one inch. Further, uncontrolled lateral motions of the brush other than its intended sliding, and in particular rotations of the brush axis during use are detrimental to brush wear. Therefore, such motions must be constrained within narrow limits. Finally, and most importantly, for high-performance applications, the sum of the friction loss and joule heat of the brush and its holder and current leads together, should not exceed 0.25 watt per ampere conducted, i.e. ~~0.25 Volt~~. These demanding conditions can be achieved with metal fiber brushes, but not with *and foil*.

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currently available brush holders, at least not at "normal" (i.e., well above cryogenic or superconducting) temperatures as prevail in almost all machinery. This is because cables of sufficient cross section to conduct the high currents at the required low losses are so stiff they significantly if not disastrously interfere with the required uniform small brush forces that must be maintained over long periods of time even while the brushes shorten through wear.

The reverse, namely, the use of metal springs for both current leads and brush force applicators, also fails on account of electrical resistances that at best compare to, and at worst greatly exceed, the electrical brush resistance. This can be seen from the following example of a current connection/brush spring loading in the form of either a cantilever or spiral spring. This is an intrinsically very favorable method, but, independent of the problem of electrical resistance, must be combined with some mechanical constraint to prevent significant uncontrolled brush movements.

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Specifically, the spring force,  $F_L$  of a uniform cantilever of width  $w$ , length  $L$  and thickness  $t$ , made of a material with Young's modulus  $E$ , and the elastic deflection  $\Delta l$  of its free end is

$$F_L = (Ewt^3/4L^3) \Delta l \quad (1).$$

The same equation, except with the factor  $1/4$  being replaced by 4, holds for the deflection of the center of a doubly supported flat spring. However, since such springs involve two sliding contacts to the current supply, and since these will have an unknown, erratic resistance besides being prone to stick-slip, doubly supported flat springs are unlikely candidates for actual current leads loading devices for electrical brushes. Lastly, for a spiral spring of  $N_H$  turns of diameter  $D$ , made of wire with diameter  $d$ , it is, with the shear modulus  $G \approx 0.4E$ ,

$$F_H = (Gd^4/8N_H D^3) \frac{\Delta l}{\Delta l} \quad (2).$$

Next, the electrical resistance for current conduction through a cantilever spring is given by

$$R_L = \rho L/wt \quad (3)$$

with  $\rho$  the electrical resistivity, and that through a helical spring of  $N_H$  turns by

5  $R_H = \rho 4N_H D/d^2 \quad (4).$

Thus, the force ( $F_L$ ) and resistance ( $R_L$ ) of a cantilever spring may be written as:

$$F_L = (Ew\Delta l / 4)(\rho/wR_L)^3 \quad (5)$$

and

$$R_L = \rho \{E\Delta l / 4Fw^2\}^{1/3} \quad (6)$$

10 while for the helical spring:

$$\checkmark R_H = \rho \{8N_H^2 E \frac{\Delta l}{A_1} / Fd^2\}^{1/3} \equiv \rho \{3.2 N_H^2 E \frac{\Delta l}{A_1} / Fd^2\}^{1/3} \quad (7).$$

Table I lists the approximate values for  $E$  ( $\approx 2.5G$  with  $G$  the shear modulus) and  $\rho$ , together with the resulting electrical resistances for a cantilever ( $R_L$ ) and a helical spring ( $R_H$ ) that would at the same time conduct the current to or from a brush and act as a spring to apply a desired brush force of  $F = 1N = 1/4$  lbs (characteristic for a  $1 \times 1 \text{cm}^2$  cross-section fiber brush

15  $\checkmark$  [7]). Herein the assumed dimensions are the best that were found for the practical case, namely  $w = 1\text{cm}$  (to permit fitting the cantilever spring to the brush),  $A_1 = 1\text{cm}$  (to permit

5mm brush wear while the brush force decreases by 50%),  $d = 0.1\text{cm}$  for both the cantilever thickness and helical spring wire diameter, and  $N_H = 3$  turns of the spiral spring. Included 20 among the candidate spring materials in Table I is TiNi, a widely used shape-memory alloy that might be considered for this application on account of its effective very low elastic modulus ( $E$ ) near maximum recoverable strain. The assumed  $E$  value in Table I for the TiNi

is at a tensile strain of  $\approx 4\%$  near the end of the plateau of its reported tensile stress curve, namely 160 MPa, and its  $\rho$ -value is that given by a manufacturer.

As seen, the resistances for a cantilever ( $R_L$ ) and helical spring ( $R_H$ ) are both too high relative to the optimal fiber brush resistance of  $\approx 300 \mu\Omega$ . Thus in high-performance metal fiber brush applications, springs cannot simultaneously conduct all of the current and provide the brush force. Unfortunately, ordinary cables act like springs with similarly unfavorable combinations of spring force to electrical resistance, as discussed hereinafter.

TABLE I

Material	E [N/cm <sup>2</sup> ]	$\rho$ [ $\mu\Omega$ cm]	$R_L$ [ $\mu\Omega$ ]	$R_H$ [ $\mu\Omega$ ]
Cu	$1.2 \times 10^7$	1.6	230	5,200
AgCu alloy	$1.2 \times 10^7$	2	290	6,500
stainless steel	$2 \times 10^7$	70	12,000	270,000
TiNi (shape memory)	$4 \times 10^5$	70	3,200	73,000

The  $R_H$  and  $R_L$  data in Table I are to be compared with the electrical fiber brush resistance,  $R_B$ . According to theory [7, eq. 20.27], well supported by experimental evidence, it is for a 1cm<sup>2</sup> brush area,

$$R_B \approx 34 [\mu\Omega \text{ cm}^2] / f\beta^{2/3} \quad [8]$$

where  $f$  is the packing fraction and  $\beta$  is the local pressure at the contact spots in units of the impression hardness of the softer side. With  $\beta$  typically between 1/3 and 1/2 and  $f$  optimally equal to 0.2,  $R_B \approx 300 \mu\Omega$ . Correspondingly, the resistances of all loading springs in the table at best compare to, or else are much larger than, the brush resistance, and hence are unsuitable for high-performance applications.

In Table I, the spring geometries are near optimum, with the cantilever spring very superior to the helical spring, and also to any doubly supported flat spring on account of the already mentioned additional contact resistances. Among the materials choices, the best are copper and copper-silver alloy, while the shape memory alloy suffers from the fundamental 5 disadvantage of a high resistivity, and it would still be unsuitable even at drastically lowered resistivity. Moreover, the spring designs are limited by the maximum allowable elastic strain before permanent deformation or fracture. Thus, whenever the relatively high Joule heat evolution is acceptable, one will from case to case have to devise suitable spring constructions to not exceed the strength of the spring material. In this instance, copper-silver 10 alloys have a considerable advantage. Such alloys have been developed for a combination of maximum strength and electrical conductivity for use in the windings of large electromagnets. Considering the very substantial research effort that has been expended in A their development, it is unlikely ~~the~~<sup>that</sup> still superior fiber brush spring materials exist. A In summary, for truly high-performance metal fiber brush tasks, metal springs will not 15 be satisfactory at ambient temperatures in a dual role of current lead and force applicator. Matters are quite different, however, at cryogenic temperatures at which metal resistivities are drastically lowered, or may even vanish in the superconducting state. At those temperatures, springs in a dual role of current leads and load applicators could be highly successful. Albeit, at any temperature or any level of Joule heat evolution, springs for brush applicators cannot 20 be used alone since they will permit too large uncontrolled lateral brush movements. These must be independently constrained, e.g., most simply by rigid tubing to guide a brush in its axial direction as it wears.

## Unintended Forces Due to Electrical Cables for Brush Current Connections

### 1) General Considerations

The above considerations imply that at least at ambient temperatures and above, metal cabling will exert uncontrolled forces on brushes, independent of the means of brush force application, that will be unacceptably high for high-performance conditions such as in planned future homopolar motors. This problem may be assessed by modeling the mechanical stiffness of a single wire or fiber in a cable as a cantilever. Accordingly, adapting eq.1 for the spring force,  $F_L$ , of a uniform cantilever of solid cross section of  $A_L = w \times t$ , made of a material with Young's modulus E, as a function of the deflection  $\Delta l$  of its free end, to a cylindrical wire of diameter  $d = t = w$ , i.e. cross section  $A_s \cong d^2$ , one obtains for the single strand in a cable:

$$F_s \cong (EA_s d^2/4L^3) \frac{\Delta l}{\Delta l} \quad (9).$$

Hence, disregarding friction among the strands, for a cable of  $N_c$  strands, and thus material cross-sectional area  $A_c = N_c A_s$ , the spring force at deflection  $\Delta l$  is at a minimum (i.e. disregarding friction among the strands in the cable which is liable to be significant),

$$F_c = N_c F_s \cong (EA_c d^2/4L^3) \frac{\Delta l}{\Delta l} \quad (10)$$

while the cable's electrical resistance from end to end is

$$R_c = \rho L/N_c d^2 \cong \rho L/A_c \quad (11).$$

As a numerical example consider the same  $1\text{cm}^2$  metal fiber brush with an approximate  $R_b = 300\mu\Omega$  resistance. For the commonly used copper cables with  $\rho = 1.6 \mu\Omega\text{cm}$  and cable length  $L = 3\text{cm}$  (for a hypothetical initial brush length of  $1.5\text{cm}$ ), the desired relatively negligible cable resistance of  $R_c = 50\mu\Omega$  requires, according to eq.11,  $A_c \cong N_c d^2 \cong 0.1\text{cm}^2$ . If, again, travel of  $\Delta l = 0.5\text{cm}$  in the course of brush wear is desired, eq.10, with  $E = 1.2 \times 10^7 \text{N/cm}^2$ , yields for the cable force

$$F_C \approx 5600 \times d^2 [N] \quad (12)$$

with,  $d$  measured in cm. With the typical fiber diameter of  $d = 0.015\text{cm}$  in ordinary flexible electrical cable, the force due to the cable would thus be  $F_C = 1.2\text{ N}$  and, hence, unacceptably large.

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### b) Electric Cables Composed of Ultra-Fine Metal Fibers

In line with the above considerations, cabling to lead electrical current to or from electrical brushes with minimal electrical resistance at minimal mechanical forces is possible by the use of ultra-fine fibers. This is demonstrated in the following TABLE II for the same cable of  $A_C = 0.1\text{cm}^2$  materials cross-section and  $N_C$  approximate number of strands, examined above, for the cases of fiber diameters  $d$  below  $101\mu\text{m}$ ,  $51\mu\text{m}$ ,  $41\mu\text{m}$ ,  $21\mu\text{m}$ ,  $11\mu\text{m}$  and down to  $2\mu\text{m}$ . The latter is the smallest likely fiber diameter because it can still be somewhat inexpensively obtained through etching from commercial multi-filamentary cables, and will not exhibit significantly increased resistivity on account of short free conduction electron paths. Thus, TABLE II indicates the approximate number of strands ( $N_C$ ) in a copper cable of  $A_C = 0.1\text{ cm}^2$  solid cross sectional area composed of  $N_C$  individual strands of diameter  $d$ , and the approximate minimum force  $F_C$  (i.e. minus the force due to friction among the strands in the cable) exerted between the two ends of that cable if they were displaced by  $\frac{\Delta L}{L} = 0.5\text{cm}$  relative to each other. The cable resistance would be  $R_C \approx 50\mu\Omega$ .

TABLE II

d	N <sub>c</sub>	F <sub>c</sub> [N]
100μm	1000	0.56
50μm	4000	0.14
40μm	6200	0.09
20μm	25,000	0.022
10μm	100,000	0.0056
2μm	$2.5 \times 10^6$	0.00022

The data in Table II indicates that at sufficiently fine fiber diameters, electrical cables of standard types of construction can be made flexible enough for leading current to and from metal fiber brushes at ambient temperatures even under the most demanding circumstances. However, in order to keep the friction forces among the individual strands low, the packing fraction of the solid material in the cables should be small, e.g. 1/3<sup>rd</sup>, so the contemplated A<sub>c</sub> = 0.1cm<sup>2</sup> cables would have a macroscopic diameter of about 0.3cm<sup>2</sup>, i.e. about 5mm diameter. This would seem still feasible for cabling to a 1cm<sup>2</sup> brush but will approach the practical limit. A further advantage of such cabling will be the opportunity to fit electrical connectors to its ends, or to branch or even fit it with electrical outlets.

In summary, electrical cables meeting the highest demands of metal fiber brushes can be made of fibers of less than 51μm diameter, with diameters below 41μm and 11μm increasingly satisfactory, and d = 2μm presumably a practical lower limit. Such cables can be used to supplement current conduction to and from brushes by other means, e.g. via loading springs as discussed in the above section, or provide the sole current path in case, for example, a compressed gas is employed to provide the mechanical brush force.

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c) Electric Cables Filled with Liquid Metal

~~The desired electrical cabling for conducting current to and from brushes at very low electrical resistance and transmitting low mechanical forces can also be constructed of liquid metal confined in flexible tubing (e.g. such as connecting shower heads to a water supply), or perhaps more simply in flexible plastic tubing.~~

Such cabling will have the same advantage as solid metal cabling constructed of ultra-fine fiber, namely that it can be readily branched or fitted with connectors and current outlets. Albeit, for the same electrical resistance per length of cable, the conducting material cross-section must be proportional to the ratio of the resistivities concerned, i.e., for a liquid metal with a ten times larger electrical resistivity (which is a reasonable or perhaps conservative estimate), the cross-section of the conducting area must be ten times larger than for the solid metal. Accordingly, since in the order of only  $1/3^{\text{rd}}$  of the solid metal cabling will typically be occupied by the fibers, the actual cross-section of the liquid metal cable exclusive of its tubing would be  $10/3$  that of the solid cable, and the cable radius  $(10/3)^{1/2} = 1.8$  times larger than for the solid cable. Accordingly, liquid metal cabling will typically be fairly massive in size. Such liquid metal cabling can be even more easily fitted with electrical connectors and can be made to branch or to be fitted with electrical "plugs" than solid cabling made of ultra-fine fibers.

d) Brush Holders Activated by Hydrostatic Fluid Pressure

- Every brush holder/brush loading device, whether for monolithic carbon-based or for *or fiber* metal fiber brushes, must fulfill three independent functions:
1. It must guide the brush along its axial direction as it wears and prevent vibrations that would seriously degrade brush wear life.

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2. As the brush wears, it must apply a nearly constant force to maintain a nearly constant pressure between the brush face and the substrate even while the brush may wear through significant lengths.
3. It must feed the brush currents to or from the brush without interfering with brush loading.

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The first function is basically the same for conventional as well as for metal fiber brushes and can be fulfilled by any low-friction guiding device (e.g. a tubing within which the brush is pushed forward). The second function is typically fulfilled by springs of various designs, including constant force springs. At any brush current, the only applicable consideration in back-fitting here is the considerably lower brush force that is required for fiber brushes. The third function is conventionally accomplished by means of flexible cables (or "pig tails"). Pig tails are always acceptable for monolithic brushes since these are never subjected to high current densities (i.e., do not require large solid cross sectional areas for connecting cables), and the mechanical brush force required for them is much higher than for fiber brushes. Pig tails also pose no problem for metal fiber brushes at low to moderate current densities, which explains why retrofitting of fiber brushes is generally possible unless current densities are high. However, as already discussed, at high brush current densities, conventional pig tails, as well as any conventional cables to bypass the loading feature, either are too stiff and interfere with the second function or they have a too high electrical resistance and as a result interfere with the critical advantage of fiber brushes, namely of permitting high current densities at low Joule and friction losses.

In the co-pending International patent application S/N 09/147,100, a brush holder has been disclosed in which both current conduction and brush force application occurs through a

hydrostatically compressed liquid metal that is fed from a central reservoir which may supply two or more similar brush holders (see Figure 1A). The present invention concerns brush holders in which the brush force is derived from a hydrostatically compressed fluid other than a liquid metal connected to a liquid metal reservoir. The fluid may comprise a liquid metal  
5 and a gas in pressure-transmitting contact therewith via a flexible membrane between them, or a gas alone. In the latter case, the requisite low-resistance current connection between the brush and the stator or other current-conducting element is made via a metal cable of ultra-fine fibers or via a liquid metal cable or both. The compressed gas together with the liquid metal may be wholly confined within a cavity in the brush holder, or the gas may be  
10 connected to a pressurized gas reservoir via a flexible tubing. Further, the brush force may be supplemented by a mechanical spring or by the reactive force of a cable used for current conduction.

If the pressurized fluid has no connection to the outside, the pressure and with it the brush force will inevitably drop with brush wear. Specifically, consider a simple, closed cylindrical internal volume  
15

$$V = Ah \quad (13)$$

of the brush holder (i.e., of cross-sectional area A and momentary height h) relative to a standard (not necessarily the initial) height  $h_o$ . If the volumes of metal and gas are

$$V_M = mAh_o \quad \text{and} \quad V_G = Ah - mAh_o \quad (14)$$

20 respectively, then the internal pressure in the holder is

$$p_G = p_{Go} V_{Go}/V_G = p_{Go} (Ah_o - Amh_o)/(Ah - Amh_o) = p_{Go} [(1 - m)/(h/h_o - m)] \quad (15)$$

yielding a brush pressure of

$$p_B = p_G A/A_B = p_{Go} (A/A_B) [(1 - m)/(h/h_o - m)] \quad (16).$$

*JMS.  
Bit* In Table III,  $p_B$  has been calculated for  $A = A_B$ ,  $h_0 = 0.4\text{ cm}$ ,  $p_B = \beta \cdot 3 [\text{N/cm}^2]$  (where,

as before,  $\beta$  is the local contact spot pressure in units of the impression hardness of the softer side, i.e. normally the fibers),  $m = 0.3$  and  $p_{G_0} = 3.64 [\text{N/cm}^2]$ . In order to keep the brush pressure within reasonable limits, however,  $\beta$  must remain within the limits of 0.7 and 0.25.

- 5 TABLE III indicates the dependence of brush pressure on wear length by the use of a brush holder of initial height  $h$  of 0.6cm partly filled with liquid metal and partly with gas at the indicated pressures. At  $h = 0.4\text{ cm}$ , the metal would occupy  $m=30\%$  of the interior holder volume. A total wear length of 9mm is possible between  $\beta = 0.7$  and 0.25. Below  $\beta = 0.25$  arcing is likely.

TABLE III

<u><math>h</math> [cm]</u>	<u><math>h/h_0</math></u>	<u><math>p_B</math> [N/cm<sup>2</sup>]</u>	<u><math>\beta</math></u>	<u>Brush Pressure</u>	<u>Wear Length [cm]</u>
0.4	1.0	3.64	1.21	too high	before start
0.45	1.125	3.09	1.03	too high	before start
0.5	1.25	2.68	0.89	too high	before start
0.6	1.5	2.12	0.707	OK	start: 0.0
0.7	1.75	1.75	0.586	OK	0.1
0.8	2.0	1.50	0.50	OK	0.2
0.9	2.25	1.31	0.436	OK	0.3
1.0	2.5	1.16	0.386	OK	0.4
1.1	2.75	1.04	0.347	OK	0.5
1.2	3.0	0.944	0.315	OK	0.7
1.5	3.75	0.739	0.246	barely OK	0.9
1.75	4.38	0.582	0.194	too low	too low
2.0	5.0	0.542	0.181	too low	too low

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B15* > One difficulty with the above design would be a relatively high electrical resistance.

since the liquid metal cross section through which the current must flow, is on average only about 10% of the brush area but it is also only about 1cm long. The advantage of this design is that it is self-contained and maintenance free, could be made cheaply, and form an integral part of brushes to be discarded with them at the end of their life.

Alternatively, the liquid metal could be replaced by a cable made of ultra-thin fibers in accordance with section (b) discussed previously. If self-contained, the pressure would drop a little slower as in the table above, and if the gas is connected to a compressed gas reservoir, the brush force would remain constant. In the first case the obtainable wear length would be ~~mildly increased, and in the second case it would be almost indefinite.~~

The various embodiments of the invention differ in any one, or a combination of any of, the following:

- JNS  
B16* > (i) ~~In the means by which the brush holder, at its top plate, is connected to the current-~~ <sup>Wall</sup>  
conducting element, among others through screws, by soldering, a dove tail, a bayonet closure, cementing or gluing (in case the electrical connection to the brush is made through cabling);
- (ii) Whether or not the gas is wholly confined within the brush holder cavity or is pressurized from an exterior reservoir;
- (iii) In the means by which the brush is fastened, directly or via a separate base plate, to ~~the bottom plate of the brush holder, among others by the same means as in (i);~~ <sup>way</sup>
- (iv) In the construction of the side wall that confines the compressed fluid and is extendable in the brush axis direction so as to permit the brush to advance as it wears.

The modifications of the side wall include, among others, bellows, telescoping tubing, flexible plastic material, spiral tubing similar to a clothes dryer exhaust hose;

(v) In the arrangement of the gas and liquid volumes when both are used;

(vi) ~~In the means for providing restraints to minimize uncontrolled brush movements other than its sliding relative to the substrate and its advance in the course of brush wear,~~  
among others through rigid prismatic tubing within which the bottom <sup>wall</sup> ~~plate~~ or the brush base plate is guided, or through rods that are parallel to the brush axis direction and one end of which is fixed to the top <sup>wall</sup> ~~plate~~ and to the bottom <sup>wall</sup> ~~plate~~ or the brush base plate, respectively;

(vii) In the number of simultaneously operated brushes;

(viii) ~~In the shape of the top and/or bottom plates, e.g. angled in conformity with the intended brush orientation relative to the current-conducting element, e.g., the stator, and the substrate;~~

(ix) Whether and in which manner the brush force due to the pressurized fluid is supplemented by mechanical means.

e) Details of the Drawings

Turning now to the drawings, wherein like reference labels designate identical or corresponding parts throughout the several views, Figure 1A is a schematic cross-sectional view, including a variety of useful optional features, of the brush holder 100 disclosed in co-pending International Application SN 09/147,100. The brush pressure is applied and the current is fed from the brush 4 by a liquid metal 8 in communion with a pressurized liquid

metal reservoir (not shown), so that the liquid metal 8 is used for both brush force application and a low-resistance current path.

Figures 2A to 2C are schematic cross-sectional views of the brush holder according to the present invention with one brush (Figure 2A) and two brushes (Figure 2B) attached to a single bottom plate 3. Figure 2C shows two bottom plates 3(1) and 3(2) for the simultaneous operation of two brushes. In more detail, Figure 2A depicts the brush 4 pressed against a substrate 7 (typically a slip ring or a commutator) in an axis direction 13 of the electrical brush 4. The brush 4 is pressed against the substrate 7 by a compressed fluid 8 contained between a top plate 1, a bottom plate 3 and side walls 2. The bottom plate 3 may be releasably attached or permanently fixed to the brush 4. The top plate 1 is connected to a current conducting element 6 via a fastener mechanism 24. The fastening mechanism 24 may be any fastener which secures the conducting element 6 to the top plate 1, such as screws, solder, cement, glue, etc. The fastening mechanism 24 should be sufficiently strong enough to keep the conducting element secured to the top plate 1 during lengthy periods of operation, etc. Current which is generated via the brush 4 sliding against the substrate 7 reaches the current conducting element 6 via the bottom plate 3, compressed fluid 8 and top plate 1.

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Figure 2B is similar to Figure 2A, but shows two brushes 4(1) and 4(2) respectively sliding along two substrates 7(1) and 7(2). Also shown in Figure 2B are two brush base plates 5(1) and 5(2) for each of the brushes 4(1) and 4(2). This differs from Figure 2A,

because in Figure 2A the bottom plate 3 serves as a brush base plate. In Figure 2B, there is the bottom plate 3 and the brush base plates 5(1) and 5(2). The brush base plates 5(1) and 5(2) are attached to the bottom plate 3 via a fastening mechanism 25(1) and 25(2), which can be any fastener sufficiently strong enough to secure the brush base plates 5(1) and 5(2) to the

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*Wall*  
At base plate 3 (i.e., similar to the fastening mechanism 24) Figure 2B also includes a rigid tubing 16 to restrict the movements of the side walls 2, and thus restrict unwanted lateral movements of the brush 4. Also shown are guides 27 between the bottom plate 3 and the rigid tubing 26 to guide the brushes 4(1) and 4(2). That is, the guides 27 prevent the interiors of the brush holder from moving around within the rigid tubing 26 so as to prevent unwanted lateral movements of the *brushes*, and thus guide the brush 4 downwards as it wears. Also shown in Figure 2B is a flexible hose 14 for pressurizing a gas 10 from outside of the brush holder. That is, using the flexible hose 14, the pressure of the gas 10 within the side walls 2 and top plate 1 and bottom plate 3, may be increased or decreased. The pressure of the gas 10 provides the *Wall* *wall* *left constant* *brushes 4(1) and 4(2)*  
A maintains the constant force against the brush 4. The pressure of the brush is in an axis direction 13 of the electrical brushes 4(1) and 4(2).

Figure 2C also illustrates a brush holder for holding two brushes 4(1) and 4(2) respectively against substrates 7(1) and 7(2). In this figure, there are two bottom plates 3(1) and 3(2) for the brushes 4(1) and 4(2). This is different than Figure 2B, in which there is only one bottom plate 3. In addition, in Figure 2C, the bottom plates 3(1) and 3(2) serve as the base plate of the brush (i.e., there is no need for the brush plates 5(1) and 5(2) shown in Figure 2B). The brushes 4(1) and 4(2) are pressed against the substrates 7(1) and 7(2) along their respective brush axes 13(1) and 13(2) via a compressed fluid 8 (rather than a compressed gas 10 as in Figure 2B). Also shown is a telescoping side wall 16, which *wear* *lengthens or shortens depending on the brush wear.* In addition, by disconnecting the holder *electrically* from the current-conducting element (6), the arrangements in Figures 2B and 2C may be adapted to lead a current between the two different substrates, instead of between the current-conducting element and the two substrates.

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cnt.*

Figures 3A to 3C show examples of different arrangements in which the brush

pressure may be applied by a liquid metal in pressure-transmitting contact with a compressed gas via flexible membranes 11. In Figure 3A, the pressurized gas 10 is confined in small spherical volumes like little balloons (i.e., flexible membranes 11) that are surrounded by a liquid metal 9. The top <sup>way</sup> plate 1, side walls 2 and bottom <sup>way</sup> plate 3 confine the flexible membranes 11 and liquid metal 9.

Figure 3B illustrates a toroidal flexible membrane 12, much like an inner tube of a car tire, filled with a compressed gas 10. The liquid metal 9 surrounds and occupies a portion in the center of the configuration (i.e., in the middle of the membrane 12). The toroidal flexible membrane 12 is secured between the top <sup>way</sup> plate 1 and bottom <sup>way</sup> plate 2 at attachment points 20.

Figure 3C illustrates the flexible membrane 11 with the compressed gas 10 surrounded by the liquid metal 9 (rather than the compressed gas 10 surrounding the liquid metal 9 as in Figure 3B). The liquid metal 9 and flexible membrane 11 (with the compressed gas 10) is contained via the top <sup>way</sup> plate 1, bottom <sup>way</sup> plate 3 and spiral side walls 19. The spiral side walls 19 are composed of spiral tubing, such as that for a clothes dryer's exhaust.

Comparing Figure 3D with Figure 3B illustrates the possibility the compressed gas 10 may be pressurized from ~~an~~ outside via a flexible hose 14. That is, as shown in Figure 3D, the pressure of the gas 10 may be controlled via the flexible hose 14 connected to an external reservoir. Thus, it is possible to maintain a constant brush force via the flexible hose 14. On the contrary, if the gas is entirely confined within the inner volume of the brush holder defined by the top <sup>way</sup> plate 1, bottom <sup>way</sup> plate 3 and side walls 2, 19 as in Figures 3A, 3B and 3C, the pressure and hence the brush force, drops as the brush wears and the indicated inner volume of the brush holder increases.

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~~Each of the side walls shown in the above figures are lengthwise extendable in the~~

brush axis direction 13 and are configured to prevent uncontrolled lateral brush motions that are detrimental to the performance of the brush. For example, depending on particular conditions, the toroidal flexible membrane 12 in Figure 3B and 3D and the spiral tubing 19 in Figure 3C should be laterally adequately stiff to prevent erratic lateral brush movements. It is also possible to further constrain erratic lateral brush movements by using the telescoping tubing shown in Figures 4A-4B (and Figure 2C).

For example, as shown in Figure 4A, the toroidal flexible membrane 12 having the compressed gas 10 therein is contained from expanding outwards via the telescoping side wall 16. The telescoping side wall 16 provides sufficient support for the toroidal flexible membrane 12 so as to prevent erratic lateral brush movements. Figure 4B is similar to Figure 4A, but shows the telescoping side wall after the brush 4 has worn. As shown, the telescoping side wall <sup>16</sup>~~16~~ naturally slides downwards in the direction of the brush axis 13 as the brush wears.

Figure 5 illustrates another embodiment in which a flexible side wall 15 made of thin plastic or rubber/elastomer sheet may be contained via rods 21 supporting the flexible side wall 15. The flexible side wall 15 may be in addition to the flexible membranes 11 and 12 or may itself contain the compressed gas 10 and/or liquid metal 9. The flexible membrane 15 is supported by the rods 21, which are attached to the top <sup>wall</sup>~~plate~~ 1 and bottom <sup>wall</sup>~~plate~~ 3. Thus, with this configuration, the erratic lateral brush movements may be prevented. The brush rods 21 are also in the brush axis direction 13 and may be made of TEFILON, for example, for ease of sliding during brush wear.

*In 3  
B 20  
cont.*

~~Figures 6A and 6B show the use of wedge-shaped top and bottom plates, singly or in combination, to angle the brush 4 relative to substrate 7 as desired. For example, as shown in Figure 6A, a wedge-shape bottom plate 23 may be releasably attached to the brush 4 to angle the brush 4 relative to the substrate 7. Figure 6A includes the flexible membrane 11 similar to that shown in Figure 3A, but also includes a side wall 17 in the form of bellows to prevent erratic lateral brush movements as discussed previously.~~

*A* ~~Figure 6B is similar to Figure 6A, but includes an additional wedge-shaped top <sup>wall</sup> <sub>plate</sub>.~~

22. ~~Figure 6B also illustrates another possible configuration of the compressed gas 10, the flexible membrane 11 and the liquid metal 9. Further, the flexible membrane 11, gas 10 and liquid metal 9 may be contained via side walls 19 composed of spiral tubing and the rigid tubing 26 so as to apply pressure to the brush 4 in an axis direction thereof. Further, it is possible that a connection to an exterior gas pressure reservoir is also included in Figure 6B (similar to that shown in Figure 3D) to maintain a constant brush force. The guides 27 may be used to guide the wedge-shaped bottom plate 23 between the rigid tubing 26 so that the brush is pressed towards the substrate 7 in a longitudinal axis direction <sup>13</sup> and to prevent erratic lateral brush movements.~~

Figures 7A-7C are perspective views of liquid metal cables made of flexible and extendable tubing filled with liquid metal and fitted with different electrical connectors. For example, Figure 7A illustrates a liquid metal cable 40 having a sidewall 18 composed of flexible tubing capped off with an electrical connector 30A. The electrical connector 30A may be a simple metal terminal which can be welded or soldered, for example, to another object (e.g., electrical device). Thus, the liquid metal cable 40 may be used to connect the top <sup>wall</sup> <sub>plate 1</sub> to the bottom <sup>wall</sup> <sub>plate 3</sub> in brush holders. This feature is discussed in more detail with

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reference Figures 8A-8C. Figure 7B illustrates a liquid metal cable 42 having a side wall 19 composed of spiral tubing and having electrical connectors 30B and 30C. The electrical connectors 30B and 30C may be conventional "plug" electrical connectors. Figure 7C is another embodiment of a liquid metal cable 44 which includes a flexible tubing 29 containing 5 the liquid metal 9 and having electrical connectors 30D and 30E.

Turning now to Figures 8A-8C. Figures 8A-8C show different brush holders in which the current is conducted through liquid metal cables and the brush force is applied by mechanical springs. For example, in Figures 8A and 8B, the liquid metal cable 46 is easily extendable and contains a helical spring 31 which applies a mechanical force between the top 10 *plate 1* and bottom *plate 3*. The liquid metal cable 46 is guided in the brush axis 13 direction by the telescoping side wall 16 while the spring 31 provides the brush force. In an initial state, the spring 31 is strongly compressed and the liquid metal cable 46 has a large average diameter (see Figure 8A). At its fullest final extension, the liquid metal cable 46 is held in place where it is fastened to the top *plate 1* and bottom *plate 3*, but is mainly constrained by 15 the helical spring 31 (See Figure 8B).

Figure 8C illustrates another example of combining liquid metal cables and mechanical springs for making electrical brush holders. As shown in Figure 8C, the spring 31 provides the brush force and is of a leaf design and is wholly outside the liquid metal 9 contained within the side walls 15. Further, the liquid metal cable 47 accommodates a 20 *distance increase between the top plate 1 and the bottom plate 3 in the course of brush wear* not through elongation as in Figures 8A and 8B, but by straightening out from a bent *position.*

*In 5  
B20  
Conceal*

Figure 9A shows a brush holder in which the pressurized fluid is the gas 10 and a current between the top <sup>Wall</sup> ~~plate~~ 1 and the brush 4 is conducted through a highly flexible cable 28 made of ultra-fine metal fibers. The gas 10 is entirely contained within an inner volume of A the brush holder via the top <sup>Wall</sup> ~~plate~~ 1 and side walls 2. Also shown is the ridging tube 26 and 5 A guides 27 to guide the wedge-shaped bottom <sup>Wall</sup> ~~plate~~ 23. Figure 9B is similar to 9A, but A includes the telescoping side wall 16 and flexible hose 14 to maintain a constant pressure of <sup>or optionally variable</sup> the gas 10. The flexible hose 14 may be connected to an exterior gas reservoir as previously discussed. Numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

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